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Investigation of Post-Implantation Annealing for Phosphorus-Implanted 4H-Silicon Carbide

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Summary: A time-dependent modeling approach for electrical activation of implanted dopant species in semiconductors is currently missing, which limits the predictability of process simulations in technology computer-aided design. In this study we investigate the time-dependent electrical activation of phosphorus-implanted silicon carbide and propose a transient model to characterize the donor concentration as a function of the annealing time, temperature, and total implanted concentration.

Keywords: Silicon carbide, Annealing, Phosphorus, Implantation, Modeling, Transient.

1. Introduction

Silicon carbide (SiC) is an attractive candidate to replace traditional silicon (Si), particularly in power electronics, in order to improve device properties and reduce internal device losses. The advantageous properties of SiC are higher thermal conductivity, higher breakdown field, and higher carrier saturation velocity. However, some fabrication steps of novel SiC devices are not yet fully optimized [1]. In particular, post-implantation steps are currently not well understood and, moreover, a time-dependent, i.e., transient, modeling approach is still completely missing.

In this study we investigate the time-dependent electrical activation of phosphorus (P)-implanted SiC and propose a transient model to characterize the donor concentration (N_D) for arbitrary annealing time (t_A), temperature (T_A), and total concentration (C_{tot}). We then perform a detailed parameter analysis and various process simulations to corroborate our approach.

2. Method

We have collected numerous experimental data in order to identify major dependencies on electrical activation of P-implanted SiC. Free carrier concentrations have been fitted with the charge neutrality equation [2], shown in Fig. 1, to obtain N_D, which have been plotted as a function of t_A for various T_A and C_{tot}, shown in Fig. 2. Based on these results, we have fitted the pre-processed data with the transient activation model, which has been inherited from the model for annealing Si-based device structures [3]:

$$\frac{dN_D}{dt} = -\frac{1}{\tau}\left(N_D - \frac{C_{tot}}{1 + C_{tot}/C_{ss}} \right), \qquad (1)$$

where C_{ss} and τ are the solid solubility and the characteristic time, respectively. In order to confirm the model predictions, we have performed simulations of ion implantation followed by the various post-implantation annealing steps, considering t_A, T_A, and C_{tot}, in order to mimic experimental setups [4].

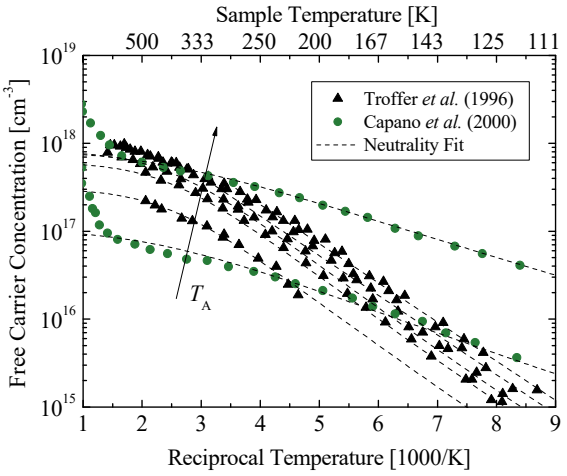

Fig. 1. Charge neutrality fits of free carrier concentrations as a function of temperature.

3. Results and Discussion

The obtained model parameters C_{ss} and τ are plotted as a function of T_A, shown in Fig. 3, and fitted with the Arrhenius equation in order to incorporate the continuous temperature dependence and to enable parameter extrapolations. The Arrhenius parameters for C_{ss} are: pre-exponential factor $Z = 7.17\times10^{23}$ cm^{-3} and activation energy $E = 2.09$ eV and for τ: $Z = 1.23\times10^{-4}$ min and $E = 1.38$ eV.

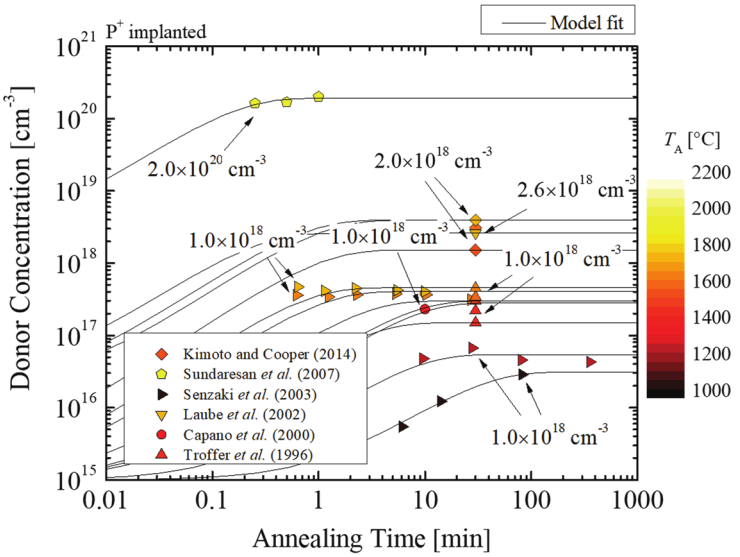

Fig. 2. Experimental data of time-dependent donor concentrations (symbols) and fits using the transient activation model (solid lines).

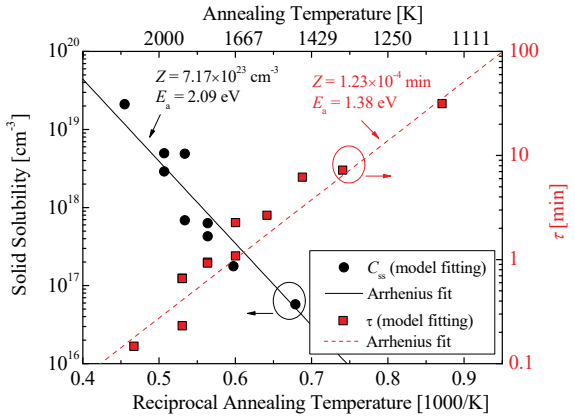

Fig. 3. Arrhenius plots of model parameter C_{ss} (left axis) and τ (right axis) obtained from the model fitting (cf. Fig. 2).

The two temperature-dependent parameters enable the characterization of N_D for P-implanted 4H-SiC over a wide range of processing variables, i.e., T_A and C_{tot}. The parameter analysis is shown in Fig. 4. Below 900 °C the activation of P is very low (i.e., < 10 %) and above 1000 °C the activation of SiC implants depends highly on C_{tot}. Furthermore, the activation process saturates for a particular T_A and C_{tot}, shown with the red shape in Fig. 4.

Finally, we have performed simulations, shown in Fig. 5, in order to validate the model. P-implantations have been conducted with the Monte Carlo ion implantation method from Silvaco's Victory Process simulator (blue solid line), which reproduce experimental doping profiles (blue symbols). The green lines indicate simulation results of the active P concentration after 30 min annealing at 1550 °C and 1700 °C. The green squares indicate the measured mean active concentration from [4]. The model confirms low activation of P-implanted SiC ($N_D < C_{tot}$), which is a consequence of the saturation effect at high doping concentrations ($C_{tot} \approx 1\times10^{20}$ cm^{-3}) for a particular T_A. Fig. 5 proves that the predicted depth profiles are in excellent agreement with the experimental data, i.e., the estimated average error is < 3 %.

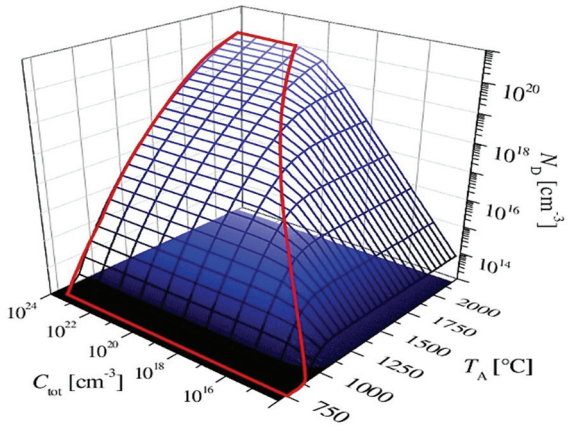

Fig. 4. Parameter analysis, i.e., model predictions of donor concentrations as a function of C_{tot} and T_A.

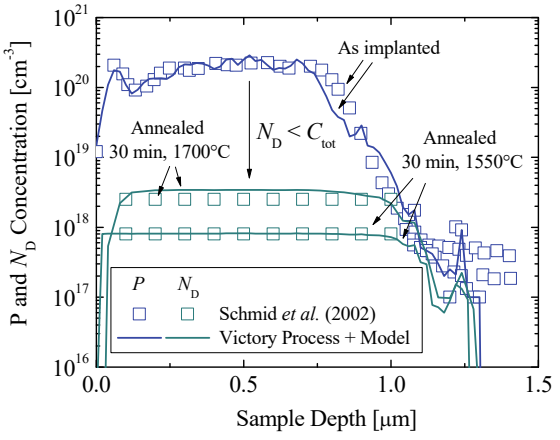

Fig. 5. Depth profiles of P and N_D from experiments (symbols) and simulations (lines).

4. Conclusions

We have proposed a transient activation model for P-implanted 4H-SiC, which has been calibrated according to experimental data from the literature. Our findings underline the importance of the proposed activation model, as 100 % activation cannot be assumed. The actual activation ratio must be accurately predicted – which is now possible – as this critically affects consecutive device performance characteristics.

Acknowledgements

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